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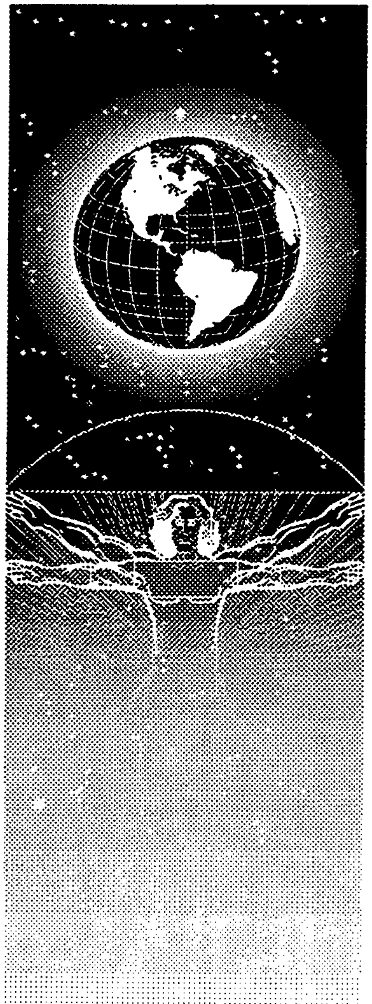

UNITED STATES AIR FORCE RESEARCH LABORATORY

Indirect Measurement of Head Orientation During Gy Acceleration

Douglas S. Brungart

September 1995

Interim Report for the Period September 1994 to September 1995

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FOR THE DIRECTOR

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For THOMAS J. MOORE, Chief
Crew Survivability and Logistics Division
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Although head-mounted technologies have the potential to significantly enhance pilot performance, they increase the mass of the helmet considerably and may increase the risk of cervical injury during emergency ejection. The lack of adequate head restraint makes the prediction of cervical injuries more complicated than other spinal injuries because the position of the head during the acceleration is unknown. A retroactive study of data from +Gy impacts of instrumented human volunteers and manikins attempted to determine head position during peak head acceleration from the direction of the head acceleration vector. The results show that the direction of this peak acceleration is very consistent across all subjects in test runs with sufficiently high energy, and that the ADAM manikin does not accurately reproduce the responses of the human head in Gy impacts.

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PREFACE

A retroactive study of head and chest accelerations in Gy impacts attempted to indirectly measure the position of the head during peak acceleration. This was accomplished by examining the direction of the resultant head acceleration vector at its maximum magnitude. The relationship between the maximum head and the maximum chest acceleration was also examined, and the human responses were compared to those of the large ADAM manikin. The author, who is in the Palace Knight program, conducted the research while working at the Escape and Impact Protection Branch between his S.M. and Ph.D. degrees.

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INTRODUCTION

Recent technological advances have allowed the integration of an increasing number of cockpit displays into the pilot's headgear. These head-mounted displays have a number of significant advantages over more traditional panel-mounted instruments, but they increase the mass of the helmet system. In an emergency escape situation, this increased head mass may increase the risk of a major head/neck injury.

Historically, the lumbar and thoracic regions of the spine have been the most likely candidates for serious injuries during ejection. Therefore the majority of impact and escape system research in the Air Force has focused on preventing and predicting spinal injuries to the lower back. The increased mass of head-mounted systems will almost certainly increase the risk of cervical injury during ejection, however, and the effects of this increased mass on the likelihood of serious injury during ejection is an important concern. Research is now underway to define the probability of significant head injury during ejection as a function of the mass and center of gravity of the helmet. The results will be used to determine the maximum acceptable mass of a helmet system, the optimal location of the center of gravity, and the best restraint systems for minimizing the potential for head/neck injuries during ejection.

One of the key differences between injury criteria in the lower back and injury criteria in the cervical region of the spine is the lack of adequate restraint for the head. The harnesses used by pilots are quite effective at immobilizing the lower portion of the back. Therefore researchers can be reasonably confident about the positioning of the lumbar region of the spine when the ejection acceleration pulse occurs. The pilot's head, however, must have a reasonable freedom of motion in order to ensure an adequate field of view. When a large acceleration occurs, the head will not be constrained and the orientation of the head during the pulse will depend on the initial orientation of the head and the direction of the acceleration vector. An important aspect of head/neck injury criteria is a knowledge of how the head moves when an acceleration pulse occurs.

This short paper describes a method of analysis that indirectly calculates the orientation of the head from the direction of the acceleration vector relative to the head at

the moment of peak acceleration during a Gy impact. The results show that the acceleration vector has an almost constant orientation relative to the head at the moment when maximum acceleration occurs. This result gives some insight into the head movement expected in a Gy impact and may be useful for the implementation of injury criteria.

Gy DATA

The data used in the analyses were collected for an experiment examining biodynamic responses during Gy acceleration. The data were collected with the Armstrong Laboratory (AL) Impulse Accelerator (3). This facility uses a gas-powered actuator to accelerate a sled down a two-rail track. The subjects, who were active-duty military volunteers, sat in a chair attached to the sled and facing perpendicular to the direction of acceleration. Sets of 3 orthogonal linear accelerometers were located in a chest pack and a mouth pack, and these accelerometers collected the X, Y, and Z accelerations of the torso and head as a function of time during the acceleration impulse.

In all cases, the acceleration pulse used was a half-sine function. Peak accelerations ranging from 4G to 7G and durations ranging from 31ms to 250ms were used in a total of 9 test cells. Table 1 shows the acceleration characteristics of the 9 test cells.

Table 1. Test Cell Characteristics

Test	*Peak*	*Duration*
A	4 G	150ms
B	5 G	150ms
C	6 G	150ms
D	7 G	150ms
E	6 G	31ms
F	6 G	64ms
G	6 G	82ms
H	6 G	210ms
I	6 G	250ms

The responses in the data are often divided into two groups: those for high energy test cells and those for low energy test cells. The energy is related to both the peak acceleration and the duration. For the purposes of the discussion of the results, cells A, E, F, and G are considered to be low energy cells. Cells C, D, H, and I are high energy cells. Cell B is somewhere in between.

A total of 15 subjects were used for the experiment, although not every subject was used for every test cell.

The subjects' weights ranged from 54.4kg (120lbs) to 98.9kg (218lbs). Data were collected for a grand total of 119 trials for all the subjects and all the test cells. Appendix A shows the test matrix of all the trials done on each subject.

The complete details of the experimental setup and data collection can be found in the report on the original Gy experiment (4).

RESULTS

When the data for the acceleration of the chest are analyzed, almost all of the acceleration occurs in the Gy direction. This results from the relatively rigid harnessing of the torso into the seat during impact. The head accelerations are not dominant in any single direction, but are usually strongest in the Gy and Gx directions. The resultant acceleration, therefore, was used for the direct analysis of the data for the head. Figures 1 and 2, on the next page, plot the resultant accelerations of the head, chest, and sled versus time for two typical tests.

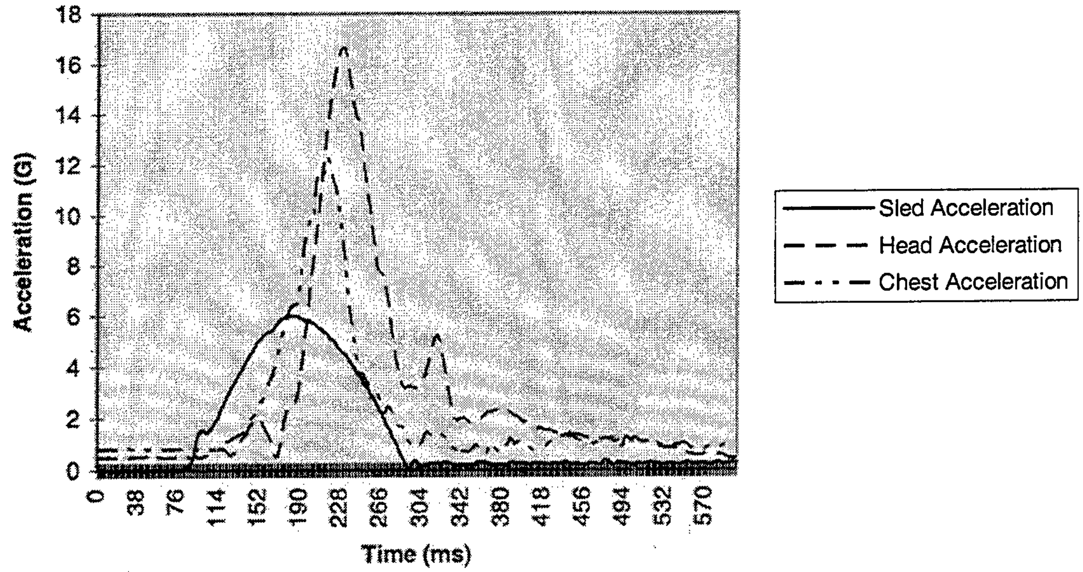


Figure 1. Head and Chest Accelerations from Test 4283 (6G Peak, 210ms Duration)

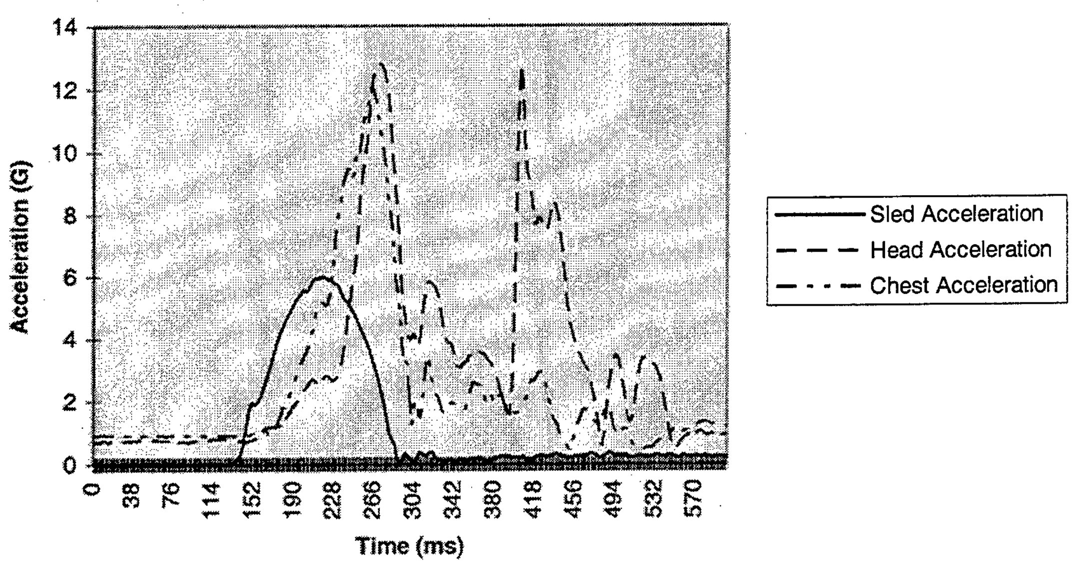


Figure 2. Head and Chest Accelerations from Test 4166 (6G Peak, 150ms Duration)

A number of observations can be made about these time waveforms. The peak acceleration of the chest is greater than the sled, and the peak acceleration of the head is greater than the chest. This is generally true for all the trials with durations greater than 100ms. The peak acceleration in the head also lags the peak acceleration of the chest in most trials by 10-15ms.

It is interesting to note that, throughout the trials examined, there was a tendency for the head and chest accelerations to initially rise together for a short interval (on the order of 20-30ms), then for the head acceleration to briefly decrease relative to the chest acceleration before rapidly increasing and peaking with a higher maximum acceleration than the chest at a slightly later time. It is likely that this pattern is caused by the subjects' attempts to maintain a fixed head position. When the acceleration impulse begins, the subject is briefly able to hold the head in a fixed position relative to the torso. This causes the head and chest accelerations to rise together initially. Once a certain threshold is reached, however, the subject can no longer maintain head position and the head moves freely for a short interval. During this interval the resultant head acceleration rises less rapidly than chest acceleration, or may even temporarily decrease, as seen in Figure 1. Finally, the head reaches its maximum extension relative to the torso and once again head acceleration rises very rapidly. A similar result is seen in the data collected with the ADAM manikin. In this case, the initial coupling of the head and chest could be explained by static friction. Once enough force is present to start the head moving, the static friction is replaced by much weaker sliding friction and the head is free to move until it reaches a mechanical stop.

Table 2. Comparison of Maximum Head and Chest Accelerations

Test Cell	Head	Human Std Dev	Chest	Data Std Dev	Ratio	ADAM Head	Data Chest	Ratio
A	10.26	±2.15	7.86	±1.11	1.31	7.40	7.64	1.03
B	12.60	±1.76	9.57	±1.29	1.32	22.47	9.03	2.48
C	15.13	±1.70	11.71	±1.23	1.29	17.93	13.03	1.38
D	17.80	±2.11	13.70	±1.58	1.20	20.32	21.99	0.92
E	3.72	±0.38	4.56	±0.72	0.82	5.78	3.84	1.51
F	9.61	±2.55	6.18	±0.79	1.56	6.35	5.71	1.11
G	10.68	±1.58	8.17	±0.82	1.31	7.50	7.73	1.03
H	15.28	±2.53	12.31	±2.07	1.24	19.43	21.62	0.90
I	14.07	±1.64	11.33	±2.34	1.24	20.42	16.78	1.22

Table 2 shows a comparison of the maximum head and chest accelerations in each test cell. The maximum resultant accelerations for each subject in a test cell were averaged together to get these results, and the standard deviations of the maximums are also shown. Data are also included from a single test with the large ADAM manikin for comparison. In all cases except the very short duration test cell E, the maximum head acceleration is greater than the maximum chest acceleration in the human tests. Although only a single manikin test is available for each cell, the manikin data in general are not a good match to the human data. The manikin accelerations tend to be smaller than the human data in the lower energy pulses and greater than the human data in the higher energy pulses. Note that the ratio of maximum head acceleration to maximum chest acceleration is relatively constant for all cells excluding E and F, ranging from 1.24 to 1.31.

Table 3. Head Acceleration Lags

Test	Head Lag (ms)	Std Dev (ms)
A	70.21	±77.37
B	34.73	±63.85
C	8.47	±14.49
D	13.75	±13.95
E	24.00	±50.04
F	113.08	±60.56
G	98.73	±75.42
H	14.55	±20.09
I	20.00	±16.00

Table 3 shows the average delay between the maximum resultant acceleration of the chest and the maximum resultant acceleration of the head, along with the standard deviations. In all of the higher energy pulses, the average

lag is between 8-20ms. In the 6G pulses longer than 100ms, the lag increases monotonically with the duration of the pulse. Notice that, in the high energy pulses, the standard deviation of the lag is lower. A likely reason for this result is that, in the lower energy pulses, the maximum sometimes occurs from a late impact between the head and the headrest after the test pulse. This can be seen in Figure 2 (acceleration from test 4166), where a strong peak occurs around 400ms because of the subject pushing his head back into the headrest after the experimental pulse. In this case, the actual peak occurs around 266ms. In some of the low energy tests, however, this impact with the headrest may be the peak acceleration. This explains the large average delay and standard deviation in the head lag for the four lowest energy pulses (A, B, F, and G).

HEAD ORIENTATION ANALYSES

One of the primary goals of this analysis was the determination of the orientation of the head when the maximum acceleration (and maximum risk of injury) occurs. This was accomplished by evaluating the direction of the head acceleration vector at the point of greatest magnitude. First, the point where the resultant acceleration of the head was greatest in a given trial was determined. Then the direction of the acceleration vector at that point, in terms of azimuth and elevation, were derived from the following formulas:

$$azimuth = \tan^{-1}\left(\frac{A_y}{A_x}\right)$$

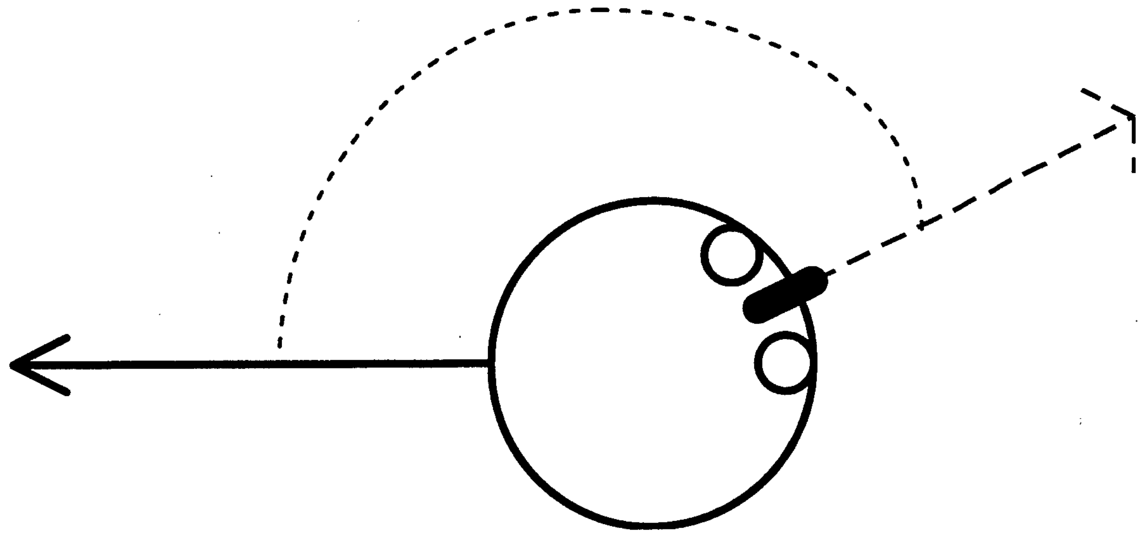
$$elevation = \tan^{-1}\left(\frac{A_z}{\sqrt{A_x^2 + A_y^2}}\right)$$

where A_x is the acceleration on the x axis, A_y is the acceleration on the y axis, and A_z is the acceleration on the z axis when the maximum value of the resultant acceleration occurs.

Table 4. Comparison of Azimuth and Elevation of Peak Head Acceleration

Test Cell	*Human Data* Azimuth	*Std Dev*	*Elevation*	*Std Dev*	*ADAM Data* Azimuth	*Elevation*
A	74.53°	63.67	-18.02°	22.36	110.91°	0.02°
B	90.49°	76.96	-8.63°	19.57	-67.58°	-6.41°
C	126.66°	7.38	-3.63°	7.14	101.71°	-39.87°
D	126.10°	7.14	-4.25°	9.64	101.02°	-42.77°
E	78.88°	78.66	17.15°	24.88	-36.87°	-2.15°
F	37.91°	61.82	-28.00°	33.96	-44.50°	-6.57°
G	47.91°	78.23	-22.59°	31.32	69.74°	-5.30°
H	126.74°	13.62	-8.86°	11.13	91.60°	-25.57°
I	126.88°	10.89	-5.57°	9.25	91.44°	-30.45°

Table 4 compares the directions of the maximum head acceleration vectors for the human data and the manikin data. In the human data, the values of azimuth and elevation for cells C, D, H, and I, the four highest energy pulses, are strikingly consistent. The average azimuth directions are within 1°, the average elevation directions are within 6°, and the standard deviations are around 10°. When the number of subjects and variety of subject sizes is considered, this consistency is very impressive. The ADAM data are similar in cells C and D, and in cells H and I. The values are quite different, however, from the human data.



This figure illustrates the head acceleration direction and its proper interpretation. The bold black arrow pointing to the left shows the direction of the acceleration of the head. In this case, it is in the Gy direction. The dashed arrow shows the direction the head is facing. Here the inertia of the head has forced it to rotate away from the acceleration. The dotted arc shows the direction of the acceleration vector in azimuth. In this case, the azimuth of the acceleration vector is approximately 140°, indicating the head has rotated approximately 50° away from the acceleration.

Figure 3. Interpretation of Acceleration Directions

Figure 3 illustrates the interpretation of these acceleration directions in azimuth. The input acceleration pulse is entirely in the Gy direction, so it is assumed that the actual direction the head is being accelerated at the point of peak acceleration is directly in the Gy direction. The inertia of the head will cause it to turn away from this acceleration, so the head can be expected to rotate to the right when the body is accelerated to the left. When this rotation occurs, the acceleration measured by the mouth pack is no longer 90° left of the subject's head, but 90° plus the rotation of the head. Thus the results shown in Table 4 can be used to approximate the rotation of the head away from the acceleration by subtracting 90°. The elevation direction gives additional information about the orientation of the head. An elevation of 0° implies the subject was level during the peak acceleration. A negative elevation

implies the subject's head was tipped away from the acceleration. A positive elevation implies the subject's head was tipped towards the acceleration. In other words, the subjects in cells C, D, H, and I consistently turned their heads 37° away from the acceleration at maximum, and tipped their heads slightly away from the acceleration. The ADAM manikin turned its head only slightly away, 10° or less, but tipped its head 25°-40° away from the acceleration. The humans were more likely to rotate their heads in response to the acceleration, while the ADAM manikin tended to tip its head. This implies that the ADAM neck joint may not be accurately representing the biodynamics of the human neck.

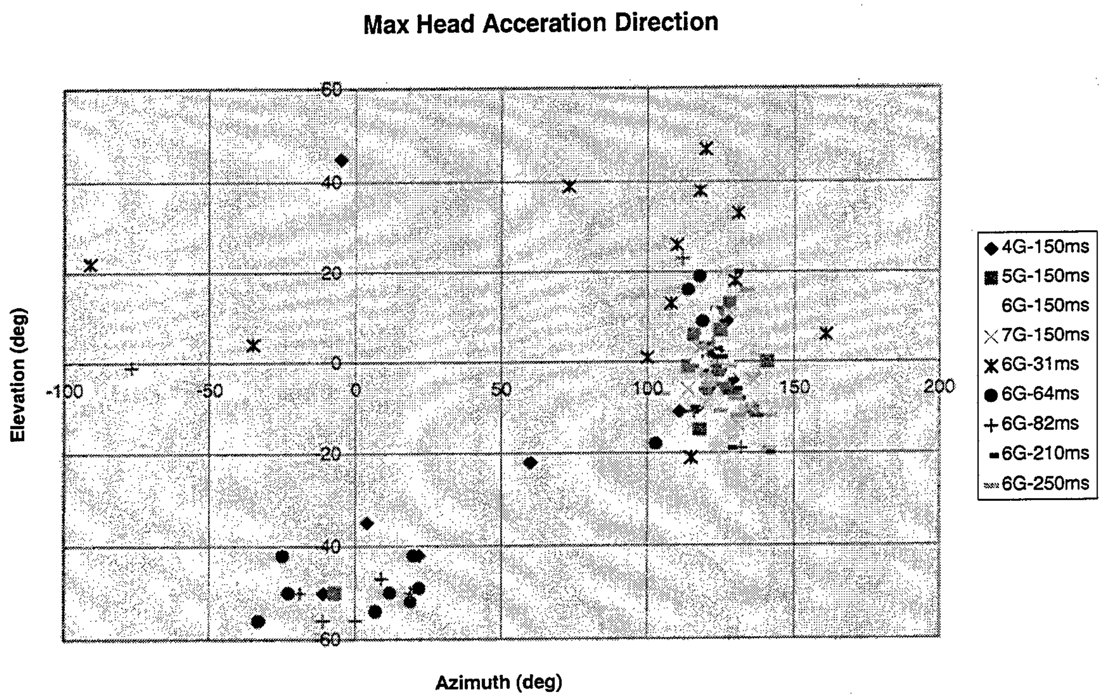


Figure 4. Scatter Plot of Head Accelerations

Figure 4 shows a scatter plot of the direction of the maximum head acceleration vector for all of the individual trials. The trials are clustered in two major areas. The first is around 0° azimuth and -50° elevation. This is consistent with an impact on the headrest of the seat with the head facing directly ahead and leaning back (looking up). These trials, which are primarily in lower energy test cells A, F and G, are probably caused by interactions between the headrest and the head well after the acceleration pulse. The second major clustering area, which contains almost every high energy trial, is around 0° in

elevation and 125° in azimuth. The very short 31ms pulse in cell E is randomly scattered.

CONCLUSIONS

This preliminary analysis of the biodynamic response of the head in a side impact shows the basic relationship between chest and head acceleration. In a sufficiently strong acceleration, the head acceleration will peak about 20ms after the chest acceleration, and will be about 30% greater than the chest acceleration. Furthermore, the acceleration will be directed approximately 35° to the side of the subject and about 5° below the horizontal plane of the head. These results can be used to verify models of the head/neck response and to assist in the development of injury criteria.

Instrumentation limitations prevented the recovery of the actual head position and orientation during the trials. Recovery of the true head position was impossible because there were only 2 cell-spot locations on the head. A third cell-spot location would have allowed a measurement of the exact head location and orientation. In future experiments, it would be interesting to measure the actual head orientation at the point of peak acceleration. This would test the assumption that the peak acceleration of the head is in the Gy direction during a Gy impact, an assumption that is crucial to the extraction of head orientation data from the acceleration vector of the head. If this assumption is true, then the consistent results for the direction of the acceleration vector can be explained if the head reaches its maximum extension during the peak acceleration and this maximum extension is consistent across many subjects. If this assumption is not true, then further investigations are required to determine why the direction of the peak acceleration is so repeatable across subjects and experimental conditions.

Finally, it is apparent that the ADAM manikin does not accurately reproduce the human head-neck response in a Gy impact. The magnitude and direction of the maximum acceleration and the ratio of the head acceleration to chest acceleration are quite different from the human data. Refinements to the ADAM neck are needed if it is expected to generate head response data that can be applied to humans.

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APPENDIX A: TEST MATRIX

Table A-1. Test Matrix

	Test Cell									
Subject	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*Weight*
C-10	X	X	X	X	X	X	X	X	X	120
R-13	X	X	X	-	X	X	-	-	-	126
C-9	X	X	X	X	X	X	X	X	X	195
A-4	X	X	X	X	X	X	X	X	X	195
A-5	X	X	X	X	X	X	X	X	X	168
D-3	X	X	X	X	X	X	X	X	X	135
H-11	X	X	X	X	X	X	X	X	X	163
H-12	X	X	X	X	X	X	X	X	X	135
D-13	X	X	X	X	X	X	X	X	X	193
D-6	X	X	X	X	X	X	X	X	X	218
B-13	X	X	X	-	X	X	X	-	X	176
B-9	X	X	X	X	X	-	X	X	X	148
B-1	X	X	X	-	X	X	-	X	-	182
F-6	X	X	X	X	-	-	-	-	-	195
G-9	X	X	X	X	-	-	-	-	X	188

Table A-1 shows the test matrix with an X for all test cells used in the processing and a - for all cells not used. The subject weights are in the far right column.